HIGH ENERGY BEAM TRANSPORT BEAMLINE FOR LEDA*

W. P. Lysenko, J. D. Gilpatrick
Los Alamos National Laboratory, Los Alamos, NM 87544 USA
M. E. Schulze
General Atomics, Los Alamos, NM 87545

Abstract

Here we describe the High Energy Beam Transport (HEBT) for the Low Energy Demonstration Accelerator (LEDA), which is part of the Accelerator Production of Tritium (APT) project. We used the TRACE 3-D linear design code[1] for the first-order design and performed r-z and 3-D particle-in-cell (PIC) simulations to study the beam distribution and halo. TRACE 3-D predicts rms beam properties well. The PIC simulations are important for determining the presence of beam halo, which is present for some tunes. We propose halo experiments to help validate our simulation codes for modeling nonlinear space charge.

1 REQUIREMENTS

The HEBT, which matches the 6.7 MeV 100 mA CW beam from the RFQ into the water-cooled nickel beamstop must meet the following requirements:

- **Match beam to beamstop**. The rms size of the beam at a point 45 inches past the entrance of the beamstop must be 44 mm in both transverse directions.
- **Provide space for equipment.** Diagnostics and other equipment take up a certain amount of length.
- **Have rms beam sizes $<$ 1/5 of aperture radius.** Inside the HEBT, we require the rms beam sizes to be less than than one-fifth of the bore radius.
- **Be insensitive to beam or quadrupole errors.** The rms beam sizes and phase-space centroids must be within the safe operating range of the beamstop.
- **Minimize beam halo generation.** Under normal operation, we do not want any beam to be scraped off in the beamline. To meet his requirement, we must ensure that no beam halo is introduced.

2 BEAM PHYSICS

We can increase the focusing strength of the lattice by decreasing the distance between quadrupoles. With sufficient external focusing, the relative strength of the space-charge force is decreased to harmless levels. The 100 mA beam current forces us to use four quadrupoles. If there were less space charge, only two or three quadrupoles would have been sufficient to match the RFQ beam to the beamstop.

* Work supported by the US DOE, Defense Programs.

When the beam reaches the last quadrupole, the bunch length is 4.5 times its original value and space charge is no longer important. In the drift to the beamstop the beam is in the zero-emittance regime ($\epsilon_x << x_{\max} x'_{\max}$). We can approximate the beam by a point source located near the final quadrupole. Emittance growth does not significantly affect the beam size. The linear TRACE 3-D code is a good predictor of beam size even though it cannot model emittance growth produced by space-charge nonlinearities.

The beam from the RFQ has a fairly uniform core and no long tails in the x and y distributions. The HEBT should preserves these qualities and not introduce any beam halo. To compute these effects, we need particle simulations, which can take into account details in the phase-space distribution and nonlinear space-charge forces.

3 DESIGN PROCEDURE

We used TRACE 3-D to design the beamline. We fixed the quadrupole positions, providing space for beamline instrumentation and diagnostics. The input beam used rms values from RFQ simulations. We specified the beam at the match point, 45 inches past the start of the beamstop, and let the TRACE 3-D optimizer determine the magnet gradients. Our results depended on the specified values of α_x and α_y at the match point. (These determine the cross-over points, which must be near the final quadrupole.) We searched for tunes having rms beam sizes everywhere less than one-fifth the bore radius.

When we ran particle simulations (see below), we found some tunes developed halos. That is, the distributions in x or y developed long, Gaussian-like tails. This happened in two situations. First, we got halos whenever the quadrupoles were too far apart. We also got halos whenever the beam size in x or y was very small at some point in the upstream part of the HEBT. Because of this effect, we accepted only tunes with fairly constant beam sizes.

4 TRACE 3-D DESIGN

Figure 1 shows the TRACE 3-D output for our standard tune. The graph shows the initial and final phase-space ellipses at the top and the transverse profiles at the bottom. The beam is traced from the RFQ end wall to the 45-inch match point, i.e., 45 inches past the start of the nickel beamstop. The scale for the x and y profiles (4.5 mm total) is appropriate for the beam in the region of the quadrupoles. The

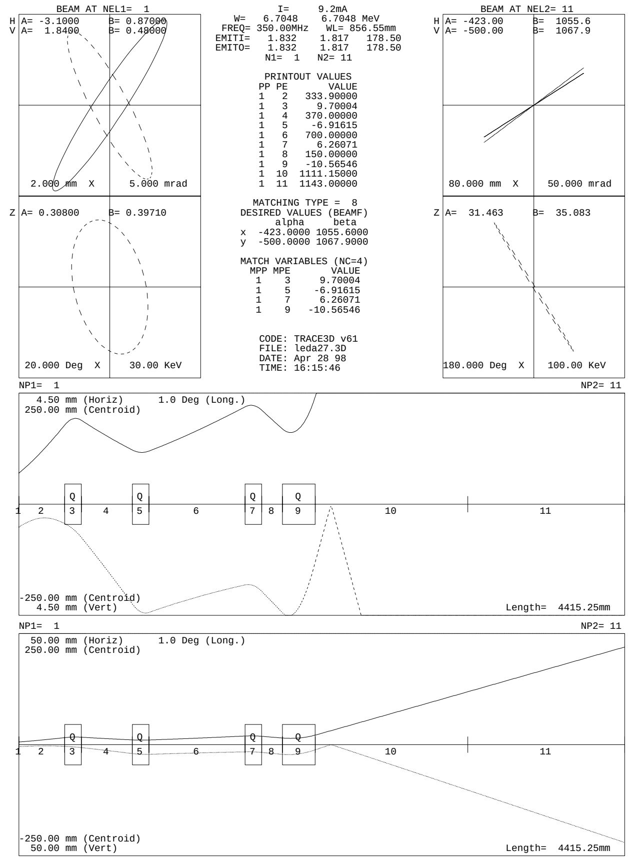

Figure 1: TRACE 3-D output for the standard tune. The beam is traced from the RFQ end wall to the 45-inch match point. The transverse profile plot is repeated at the bottom with a larger scale to show the beam in the beamstop.

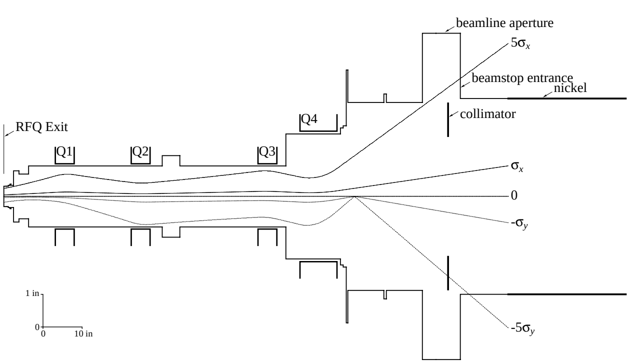

Figure 2: The 1-σ (rms) and 5-σ beam profiles compared to the minimum aperture in the HEBT beamline.

lower part of Fig. 1 shows the profile with a scale of 50 mm total to show the expansion of the beam in the beamstop. In our TRACE 3-D simulations, we use rms emittances and thus the plots show the rms beam sizes. The current we use (9.19 mA) is the actual current (103 mA) divided by $5/\sqrt{5}$. Figure 2 shows the rms and 5×rms profiles together with the minimum beam apertures in the HEBT.

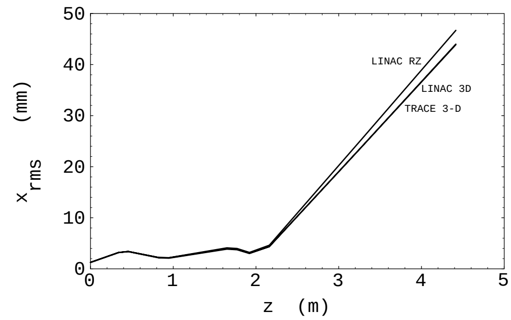

Figure 3: Rms value of x as a function of z for the r-z and 3-D PIC simulation using the LINAC code and the TRACE 3-D code. The two 3-D codes produced similar results.

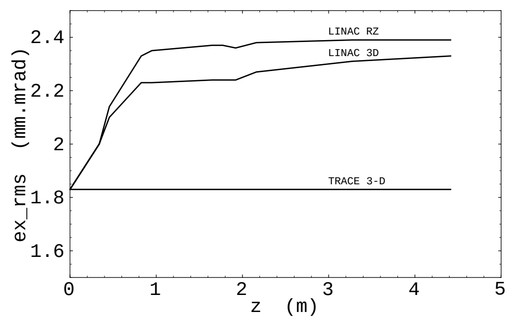

Figure 4: Rms value of x emittance as function of z.

5 SENSITIVITY STUDY

We studied the sensitivity of the beam at the beamstop to errors in the quadrupoles (strengths and offsets) and to various errors in the input beam. We found no errors that could not be handled by our diagnostics and control system. The beam spot at the beamdump depends on the beam current. While lower-current beams have a smaller spot size, the current density (current per unit area) is smaller than for the normal, full-current beam. There is no need to retune for different currents.

6 PIC SIMULATIONS

We verified our TRACE 3-D designs with particle-in-cell (PIC) simulations. We ran r-z and fully 3-D PIC simulations. Figure 3 shows $x_{\rm rms}$ as a function of z for our standard tune as predicted by TRACE 3-D and the r-z and 3-D versions of the PIC code LINAC[2]. The two 3-D codes agree very well but the r-z code produces slightly different results. As Fig. 4 shows, there is about a 30% emittance growth. This did not affect the TRACE 3-D result for the beam size because the emittance is so small. The conclusion is that 3-D effects are important but nonlinearities are not in predicting rms beam size. Our TRACE 3-D designs produce the correct rms beam at the match point.

PIC simulations are essential in determining if our tunes generate halos. Figure 5 shows the TRACE 3-D output for

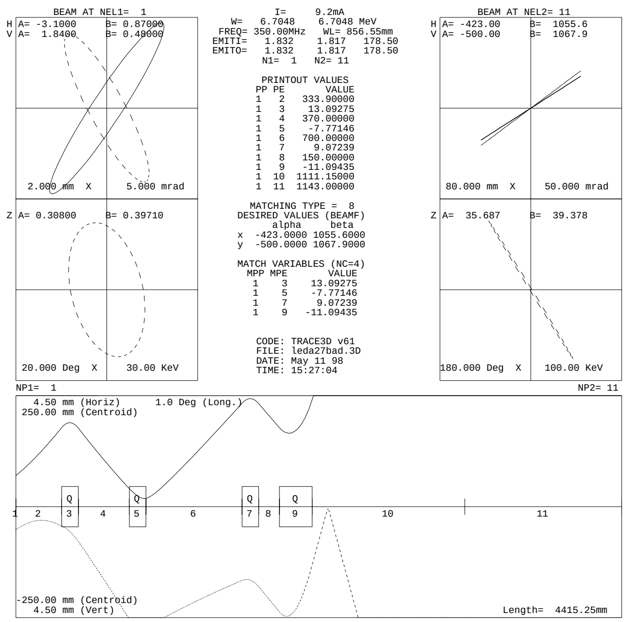

Figure 5: TRACE 3-D output for a bad tune, which has a halo in the x-direction. Halo-generating tunes have a small waist in the upstream part of the beamline.

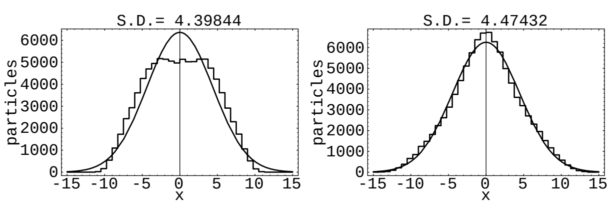

Figure 6: Beam profiles in the x-direction at the match point for the standard tune (left) and the bad tune (right).

another tune that produces the same beam at the 45-inch match point. Only the quadrupole settings are different. The input and final beams and all lengths are the same as before. We see that the beam has a small waist in x early in the HEBT. We find this characteristic is always associated with the existence of a halo. Figure 6 shows the x distribution in a 3-D PIC simulation at the 45-inch match point for both the standard and bad tunes. Also shown are Gaussians having the same rms values as the actual distributions. The halo is generated in the first part of the second quadrupole, just before the waist. Figure 7 shows the phase-space scatter plots in the x direction at the beginning and the center of Q2. We see that the distribution becomes very nonelliptical because of the nonlinear space-charge forces.

7 HALO EXPERIMENTS

Table 1 shows properties of the x profile at the wire scanner for both the standard tune and the bad tune. Also shown are a uniform (rectangular) and Gaussian distribution having the same sigma ($<x^2>^{1/2}$) value. A good way to characterize whether or not we have a halo is to determine the

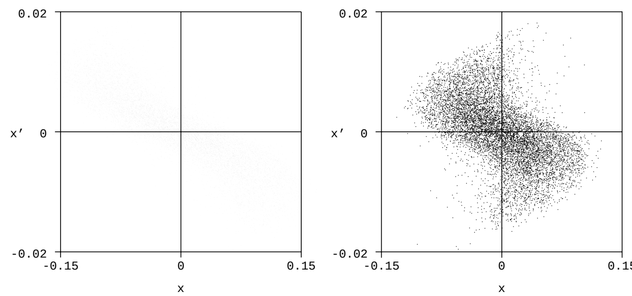

Figure 7: The x-x' phase-space scatter plots for bad tune at start of Q2 (left) and center of Q2 (right).

Table 1: Properties of x distributions at wire-scanner.

Beam	$<x^2>^{1/2}$ (mm)	$x_{\max}$ (mm)	$<x^4>/<x^2>^2$
Uniform	16	28	1.8
Gaussian	16	∞	3.0
Standard	16	41	2.2
Bad	16	56	2.9

kurtosis of the x or y distribution. The kurtosis is simply the fourth moment of the distribution, normalized by the square of the second moment to obtain a dimensionless quantity. The fourth moment depends on the whole beam distribution. It should be easy to measure even if the wire scanner does not have a large dynamic range (the amount of beam for the bad tune that is past the maximum $|x|$ value of the standard tune is only 0.35%).

8 CONCLUSION

Our HEBT design meets all readily quantifiable requirements. Our 3-D PIC simulations verify that the TRACE 3-D design code can accurately predict rms beam properties. Nonlinear space-charge effects are important, however. We have found that having adequate focusing (no less than four quadrupoles) and a good tune are essential to avoid halo formation, which could result in undesirable particle losses before the beamstop.

The codes clearly indicate when halo formation occurs. We therefore propose that we do some halo experiments at LEDA. We can obtain the required information from the wire-scanner data. If we verify the simulations' predictions about the differences between the good and bad tunes, we will have greatly increased confidence in the ability of our codes to correctly model nonlinear space-charge effects.

9 REFERENCES

[1] D.P. Rusthoi, W.P. Lysenko, and K.R. Crandall, "Further improvements in TRACE 3-D," Proceedings of the 1997 Particle Accelerator Conference.

[2] K. Crandall and R. Ryne, private communication, 1998.